The Physics of New $U(1)'$ Gauge Bosons

Paul Langacker

Institute for Advanced Study ,Princeton, NJ 08540

Abstract. Additional Z' gauge bosons are predicted by a wide variety of extensions of the standard model (SM). Possibilities include TeV-scale bosons with electroweak coupling, very light bosons which nearly decouple from the standard model particles, and bosons which communicate with a quasi-hidden sector. A broad survey is given of the theoretical possibilities and of the physics implications for particle physics and cosmology. Several novel examples, including light Z's suggested by PAMELA, Stueckelberg Z's, and Z's associated with the mediation of supersymmetry breaking, are described.

MOTIVATIONS

An additional Z' gauge boson is one of the best motivated extensions of the standard model or MSSM. String and grand unified theories often involve large underlying groups, or (in the case of Type IIa constructions) promote $SU(n)$ groups to $U(n)$. In many cases, it is more difficult to break the $U(1)'$ generators than the non-abelian ones, implying that extra Z's may survive to low energies as accidental remnants of the symmetry breaking. Also, many supersymmetric $U(1)'$ models provide a natural solution to the μ problem. In that case both the $SU(2) \times U(1)$ and $U(1)'$ breaking scales are set by SUSY breaking scale (unless the breaking is associated with a flat direction), so one naturally expects the Z' mass to be comparable to the electroweak scale, up to an order of magnitude or so. Similarly, alternative electroweak models (such as left-right symmetry) or alternatives to the elementary Higgs mechanisms, e.g., dynamical symmetry breaking or Little Higgs models, involve new TeV scale physics and extended gauge groups that often lead to new TeV-scale Z's. Models in which the standard model gauge bosons can propagate in large and/or warped extra dimensions involve Kaluza-Klein excitations, with $M \sim R^{-1} \sim 2\,\text{TeV} \times (10^{-17}\text{cm}/R)$ in the large dimension case. Another aspect is that Z's may provide a weak coupling between the ordinary sector of matter and other sectors associated with dark matter or with supersymmetry breaking. Finally, the existence of an extra Z', especially at the TeV scale, would have extensive implications for collider physics and cosmology. In this talk I will describe selected recent developments. More general treatments may be found in several recent reviews [1, 2, 3].

THE STANDARD MODEL WITH ADDITIONAL $U(1)'$S

The interactions of the photon (A), Z (i.e., Z_1^0) and other flavor-diagonal neutral gauge bosons with fermions is

$$- \mathscr{L}_{NC} = \underbrace{eJ_{em}^\mu A_\mu + g_1 J_1^\mu Z_{1\mu}^0}_{SM} + \sum_{\alpha=2}^{n+1} g_\alpha J_\alpha^\mu Z_{\alpha\mu}^0, \tag{1}$$

where g_α are the gauge couplings (with $g_1 = g/\cos\theta_W$), and the currents are

$$J_\alpha^\mu = \sum_i \bar{f}_i \gamma^\mu [\varepsilon_L^\alpha(i)P_L + \varepsilon_R^\alpha(i)P_R]f_i. \tag{2}$$

$\varepsilon_{L,R}^\alpha(i)$ are the $U(1)_\alpha$ charges of the left- and right-handed components of fermion f_i, and the theory is chiral for $\varepsilon_L^\alpha(i) \neq \varepsilon_R^\alpha(i)$. It is often convenient to instead specify the charges Q_α for the left-chiral fermion f_L and and left-chiral antifermion f_L^c,

$$Q_{\alpha f} = \varepsilon_L^\alpha(f) \qquad Q_{\alpha f^c} = -\varepsilon_R^\alpha(f). \tag{3}$$

For example, the SM charges for the u_L and u_L^c are $Q_{1u} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$ and $Q_{1u^c} = +\frac{2}{3}\sin^2\theta_W$. One can similarly define the $U(1)_\alpha$ charge of the scalar field ϕ as $Q_{\alpha\phi}$.

For a single extra Z', the $Z - Z'$ mass matrix after symmetry breaking is

$$M_{Z-Z'}^2 = \begin{pmatrix} M_{Z^0}^2 & \Delta^2 \\ \Delta^2 & M_{Z'}^2 \end{pmatrix}. \tag{4}$$

If, for example, the symmetry breaking is due to an $SU(2)$-singlet S and two doublets $\phi_u = \begin{pmatrix} \phi_u^0 \\ \phi_u^- \end{pmatrix}$, $\phi_d = \begin{pmatrix} \phi_d^+ \\ \phi_d^0 \end{pmatrix}$, then

$$\begin{aligned} M_{Z^0}^2 &= \frac{1}{4}g_1^2(|v_u|^2 + |v_d|^2), \qquad \Delta^2 = \frac{1}{2}g_1g_2(Q_u|v_u|^2 - Q_d|v_d|^2) \\ M_{Z'}^2 &= g_2^2(Q_u^2|v_u|^2 + Q_d^2|v_d|^2 + Q_S^2|s|^2), \end{aligned} \tag{5}$$

where

$$v_{u,d} \equiv \sqrt{2}\langle\phi_{u,d}^0\rangle, \qquad s = \sqrt{2}\langle S\rangle, \qquad v^2 = (|v_u|^2 + |v_d|^2) \sim (246\,\text{GeV})^2. \tag{6}$$

The physical mass eigenvalues are $M_{1,2}^2$, and the mixing angle θ is given by $\tan^2\theta = (M_{Z^0}^2 - M_1^2)/(M_2^2 - M_{Z^0}^2)$. In the important special case $M_{Z'} \gg (M_{Z^0}, |\Delta|)$ one finds

$$M_1^2 \sim M_{Z^0}^2 - \frac{\Delta^4}{M_{Z'}^2} \ll M_2^2 \qquad M_2^2 \sim M_{Z'}^2$$

$$\theta \sim -\frac{\Delta^2}{M_{Z'}^2} \sim C\frac{g_2}{g_1}\frac{M_1^2}{M_2^2} \quad \text{with} \quad C = 2\left[\frac{Q_u|v_u|^2 - Q_d|v_d|^2}{|v_u|^2 + |v_d|^2}\right]. \tag{7}$$

We have so far implicitly assumed canonical kinetic energy terms for the $U(1)$ gauge bosons. However, $U(1)$ gauge invariance allow a more general kinetic mixing [4],

$$\mathcal{L}_{kin} \rightarrow -\frac{1}{4}F_1^{0\mu\nu}F_{1\mu\nu}^0 - \frac{1}{4}F_2^{0\mu\nu}F_{2\mu\nu}^0 - \frac{\sin\chi}{2}F_1^{0\mu\nu}F_{2\mu\nu}^0 \tag{8}$$

for $U(1)_1 \times U(1)_2$. Such terms are usually absent initially, but a (usually small) χ may be induced by loops, e.g., from nondegenerate heavy particles, in running couplings if heavy particles decouple, or at the string level. The kinetic terms may be put in canonical form by the non-unitary transformation

$$\begin{pmatrix} Z_{1\mu}^0 \\ Z_{2\mu}^0 \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & 1/\cos\chi \end{pmatrix} \begin{pmatrix} \hat{Z}_{1\mu}^0 \\ \hat{Z}_{2\mu}^0 \end{pmatrix}, \tag{9}$$

where the $\hat{Z}_\alpha^0$ may still undergo ordinary mass mixing, as in (4). The kinetic mixing has a negligible effect on masses for $|M_{Z_1}^2| \ll |M_{Z_2}^2|$ and $|\chi| \ll 1$, but the current coupling to the heavier boson is shifted,

$$-\mathcal{L} \rightarrow g_1 J_1^\mu \hat{Z}_{1\mu} + (g_2 J_2^\mu - g_1\chi J_1^\mu)\hat{Z}_{2\mu}. \tag{10}$$

MODELS

There are an enormous number of models (e.g., [1]), distinguished by their gauge coupling g_2, their mass scale, their charges Q_2, the exotic fermions needed for anomaly cancellation, kinetic mixing, possible couplings to hidden sectors, whether one assumes supersymmetry, etc, and there is no simple general parametrization. Some of the major classes include:

- "Canonical" TeV-scale models with electroweak strength couplings, including the sequential Z_{SM} model with the same couplings to fermions as the Z, models based on T_{3R} and $B - L$, E_6 models, and minimal gauge unification models.
- Those based on new TeV scale dynamics, such as Little Higgs models, un-unified models, dynamical symmetry breaking models, e.g., with strong $t\bar{t}$ coupling, etc.
- Kaluza-Klein excitations of the SM gauge bosons in models with large and/or warped extra dimensions.
- Models in which the Z' is decoupled from some or all of the SM particles, such as leptophobic, fermiophobic or weak coupling models. These may have a low scale or even massless Z'.
- Models in which the Z' couples to a hidden sector, e.g., associated with dark matter or supersymmetry breaking. Such a Z' may (almost) decouple from the SM particles and serve as a weakly coupled "portal" to the hidden sector, or may couple to both sectors, e.g., to mediate supersymmetry breaking.
- Supersymmetric models with a secluded or intermediate scale Z', e.g., associated with (approximately) flat directions, small Dirac m_ν from higher-dimensional operators, etc.

- Models with family-nonuniversal couplings, leading to Z'-mediated FCNC.
- String derived models, which may be lead to Z' coupled to T_{3R}, $B - L$, or E_6 couplings, or may appear "random".
- Stückelberg models [5], which allow a Z' mass without spontaneous symmetry breaking.
- Anomalous $U(1)'$ models, which may be relevant to some string theories involving large dimensions.

RECENT DEVELOPMENTS

There has been much recent work on models in which a Z' connects the SM particles to an otherwise hidden or dark sector. In some cases, the $U(1)'$ mainly couples to the hidden sector, with a weak connection to the SM via small kinetic mixing (for a review, see [6]), higher-dimensional operators, D-terms, Higgs fields, Chern-Simons $Z'Z\gamma$ couplings, etc., leading to the possibility of invisible Z' decays to hidden sector particles and/or suppressed decays to the SM particles. Alternatively, the $U(1)'$ may couple directly to both sectors (as is common in string constructions), such as in Z' mediation models. Here, we mention several examples.

A massless Z'

An interesting possibility is that there are two massless gauge bosons, the photon (A) and a new Z', presumably with no direct couplings to the SM sector. A small kinetic mixing of the form (8) could induce the interaction
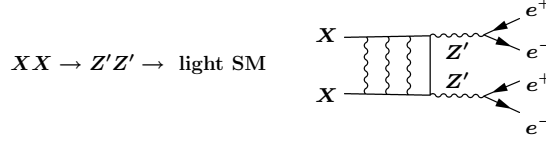
$$-\mathscr{L} \to e(J^{em} - \frac{g_2\chi}{e}J_2^\mu)A_\mu + g_2 J_2^\mu Z'_\mu, \tag{11}$$

which differs from (10) since both gauge bosons are massless. In (11), $g_2 J_2$ describes possible interactions of the Z' with a hidden sector. For small χ, e.g., $\chi = \mathcal{O}(10^{-3})$ the kinetic mixing induces effective milli-electric charges for the hidden sector particles [4]. Alternatively, the sectors could be connected by higher-dimensional operators [7], leading, e.g., to $\mu \to eZ'$. Implications of such models for dark matter have been studied in [8, 9], possible string origins in [6, 10], and recent experimental and cosmological constraints in [11, 12, 13].

An MeV/GeV Z'

A related possibility is that a Z' in the MeV-GeV range (sometimes referred to as a U-boson [14, 15]) acquires a weak coupling to J_{em} by kinetic mixing. Such a particle could have implications for or is constrained by, e.g., $g_\mu - 2$, $e^+e^- \to U\gamma \to e^+e^-\gamma$, and even the HyperCP events [16, 17]. U-bosons have received much recent attention as a possible implementation of a class of models that could account for the PAMELA positron excess

(if it is not astrophysical in origin) [18, 19]. The idea is that a heavy (hundreds of GeV) dark matter particle X could annihilate into GeV Z' s, which would decay preferentially into light SM particles because of its small mass. The necessary large enhancement in the XX annihilation cross section (needed in all such models) could be accounted for by the Sommerfeld enhancement (from the distortion of the wave functions at low energy), due to repeated Z' exchange

$$XX \to Z'Z' \to \text{ light SM}$$

The same model could also account for the DAMA results if the Z' couples inelastically [20], e.g., to $X_1 X_2$ where there is a small ($\mathcal{O}(100\,\text{keV})$) mass splitting between the X_1 and X_2. At the LHC, such a light Z' would be highly boosted, leading to narrow "lepton jets" from $Z' \to \ell^+ \ell^-$, possible displaced vertices, etc. [21, 22, 23, 24, 25, 26, 27, 28, 29].

The Stückelberg extension of the Standard Model

For a $U(1)'$ (but not a non-abelian theory) it is possible to generate a (Stückelberg) Z' mass [5] without breaking gauge invariance by writing

$$\mathscr{L} = -\frac{1}{4}C^{\mu\nu}C_{\mu\nu} - \frac{1}{2}(mC^\mu + \partial^\mu\sigma)(mC_\mu + \partial_\mu\sigma), \tag{12}$$

where C_μ is the gauge field which gauge transforms as $\Delta C_\mu = \partial_\mu\beta$, $C^{\mu\nu}$ is the invariant field strength, and σ is an axion-like scalar, with $\Delta\sigma = -m\beta$. The gauge fixing terms cancel the $C_\mu\partial^\mu\sigma$ cross term, leaving a massive vector and a decoupled σ, i.e., without a physical Higgs boson. Such terms can arise in several ways, including in five-dimensional $U(1)$ models, as the $(\mu^2, \lambda) \to \infty$ limit of the Higgs model with $(-\mu^2/\lambda)$ fixed; or in string/brane models with a Green-Schwarz mechanism [30, 31, 32].

Recently, a Stückelberg extension of the SM has been proposed [33, 34], with

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}C^{\mu\nu}C_{\mu\nu} - \frac{1}{2}(m_2 C^\mu + m_1 B^\mu + \partial^\mu\sigma)^2 + g_X C_\mu J_X^\mu, \tag{13}$$
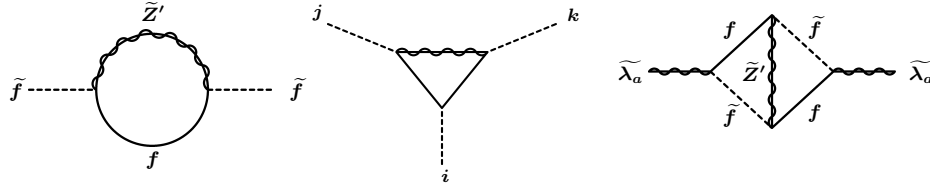
where B is the SM $U(1)_Y$ boson, the new gauge field C couples to a hidden sector current J_X with coupling g_X, and the ratio $\phi \sim m_1/m_2$ is assumed to be small. The Stückelberg term generates a mass $\sim m_2$ for the heavy boson ($Z' \sim C$). The photon remains massless but couples to the hidden sector with a tiny effective charge $\propto \phi$. Similarly, the Z' couples to ordinary matter with a suppressed coupling $\propto \phi$. If there are no open decay channels into the (unsuppressed) hidden sector, this will imply a very narrow Z', e.g., with $M_{Z'}$ in the 100 GeV-TeV range. There have been extensions of the model [30] to the MSSM and to include kinetic mixing. Dark matter interpretations can involve either milli-weak or milli-charged particles, and it is possible to account for the PAMELA events.

Hidden Valley Models

Hidden valley models [35, 36] assume the existence of a strongly-coupled hidden sector which is connected to the SM particles by a weakly coupled Z' or other suppressed interactions. Hidden valley neutral bound state particles may escape the detector or may decay back to SM particles with displaced vertices. A Z' which mainly decays to invisible particles may be detected by associated production, $pp \rightarrow ZZ', \gamma Z'$ [37].

Z'- mediated Supersymmetry Breaking

Z'-mediation [38, 39] is a top-down motivated scenario, which can occur when a new $U(1)'$ couples to both the SM sector and the supersymmetry breaking sector, allowing supersymmetry breaking to communicated by the $M_{Z'} - M_{\tilde{Z}'}$ mass difference. For example, if the $U(1)'$ gauge symmetry is *not* broken in the hidden sector, one may still generate a Z' gaugino mass at a supersymmetry breaking scale Λ_S by its (model dependent) couplings to the hidden sector particles. Then scalar mass-squares and A terms for the SM particles can be generated at one loop-level by the couplings to the Z' and $\tilde{Z}'$, and the MSSM gaugino masses at two-loop level:

The ratio of the scalar to SM gaugino masses generated in this way is $m_{\tilde{f}_i}/M_a \sim (4\pi)^3 \sim 1000$. Since the SM gaugino masses need to be sufficiently heavy, $M_a \gtrsim 100$ GeV, this suggests two options:

- The Z' mediation accounts for all of the soft breaking. For $M_a \sim 100 - 1000$ GeV one then requires scalar masses ~ 100 TeV. The electroweak scale must be achieved by a fine-tuning, yielding a mini version of split supersymmetry (the original version [40] typically assumed $m_{\tilde{f}} \sim 10^9$ GeV). Only the gauginos, a single Higgs, and possibly the Z' would be observable at the LHC.
- The scalar masses could be at 100-1000 GeV. The SM gauginos would have to acquire mass by some other mechanism. For example, the combination with anomaly mediation may yield a realistic spectrum [41, 42].

IMPLICATIONS

Finally, we comment on a TeV-scale Z' with electroweak scale couplings. The implications of such a discovery would go far beyond the existence of a new vector particle.

Here, we list some of the possibilities (see [1] for more complete references).

- There are stringent limits on $M_{Z'}$ and on $Z-Z'$ mixing from weak neutral current, Z-pole, and LEP 2 experiments, and from direct searches by CDF and D0 at the Tevatron, yielding $M_{Z'} > 800 - 900$ GeV for typical models with electroweak coupling, and $|\theta| < $ few $\times 10^{-3}$ (e.g., [43]). The LHC has a discovery potential to $\sim 4-5$ TeV through $pp \to Z' \to e^+e^-, \mu^+\mu^-, jj, \bar{b}b, \bar{t}t, e\mu, \tau^+\tau^-$, and should be able to make diagnostic studies of the Z' couplings up to $M_{Z'} \sim 2-2.5$ TeV. Possible probes include forward-backward asymmetries; rapidity distributions; lineshape variables; associated production of $Z'Z, Z'W, Z'\gamma$; rare (but enhanced) decays such as $Z' \to W\bar{f}_1 f_2$ involving a radiated W; and decays such as $Z' \to W^+W^-, Zh, 3Z$, or $W^\pm H^\mp$, in which the small mixing is compensated by the longitudinal W, Z enhancement. (See [1, 2, 3] for the classic references, and [44, 45, 46, 47] for recent developments.)
- A $U(1)'$ can yield a natural solution to μ problem in supersymmetry, by forbidding an elementary μ term but allowing the superpotential term $W \sim \lambda_S S H_u H_d$, where S is a SM singlet charged under the $U(1)'$. This induces an effective μ parameter $\mu_{eff} = \lambda_S \langle S \rangle$, which is usually of the same scale as the soft supersymmetry breaking parameters. This mechanism is similar to the NMSSM (e.g., [48]), but is automatically free of induced tadpole and domain wall problems.
- TeV scale $U(1)'$ models generally involve an extended Higgs sector, requiring at least a SM singlet S to break the $U(1)'$ symmetry. New F and D-term contributions can relax the theoretical upper limit of ~ 130 GeV on the lightest Higgs scalar in the MSSM up to ~ 150 GeV, and smaller values of $\tan\beta$, e.g. ~ 1, become possible. Conversely, doublet-singlet mixing can allow a Higgs lighter than the direct SM and MSSM limits. Such mixing as well as the extended neutralino sector can lead to non-standard collider signatures [49, 50].
- $U(1)'$ models also have extended neutralino sectors [51], involving at least the $\tilde{Z}'$ gaugino and the $\tilde{S}$ singlino, allowing non-standard couplings (e.g., light singlino-dominated), extended cascades, and modified possibilities for cold dark matter, $g_\mu - 2$, etc.
- Most $U(1)'$ models (with the exception of those involving $B-L$) require new exotic fermions to cancel anomalies. These are usually non-chiral with respect to the SM (to avoid precision electroweak constraints) but chiral under the $U(1)'$. A typical example is a pair of $SU(2)$-singlet colored quarks $D_{L,R}$ with charge $-1/3$. Such exotics may decay by mixing, although that is often forbidden by R-parity. They may also decay by diquark or leptoquark couplings, or they be quasi-stable, decaying by higher-dimensional operators [52, 53].
- A heavy Z' may decay efficiently into sparticles, exotics, etc., constituting a "SUSY factory" [54, 55, 56, 57, 58].
- The $U(1)'$ charges may be family non-universal (especially in string constructions), leading to FCNC when fermion mixings are turned on. The limits from K and μ decays and interactions are sufficiently strong that only the third family is likely to be non-universal [59]. Third family non-universality may lead to significant tree-level effects [60], e.g., in $B_s - \bar{B}_s$ mixing or in charmless B_d decays, competing with

SM loops, or with enhanced loops in the MSSM with large $\tan\beta$.

- A TeV-scale $U(1)'$ symmetry places new constraints on neutrino mass generation. Various versions allow or exclude Type I or II seesaws, extended seesaws, or small Dirac masses by higher-dimensional operators [53, 61, 62, 63, 64]; small Dirac masses by non-holomorphic soft terms [65]; either Majorana (seesaw) or small Dirac masses by string instantons [66, 67]; and Majorana masses associated with spontaneous R-parity violation [68].

- Electroweak baryogenesis is relatively easy to implement because of the cubic A term associated with the effective μ parameter and possible tree-level CP violation in the Higgs sector (which is not significantly constrained by EDMs) [69].

CONCLUSIONS

- New Z' s are extremely well motivated.
- $M_{Z'}$ at the TeV scale is likely, especially in supersymmetry and alternative EWSB models.
- The LHC has a discovery potential to $\sim 4-5$ TeV, and diagnostic capabilities to $\sim 2-2.5$ TeV.
- There are major implications of a TeV-scale Z' for particle physics and cosmology.
- A Z' (massless, of at the GeV or TeV scale) could be a portal to a hidden and/or dark sector.

ACKNOWLEDGMENTS

REFERENCES

1. P. Langacker, *Rev. Mod. Phys.* **81**, 1199–1228 (2009), `arXiv:0801.1345 [hep-ph]`.
2. T. G. Rizzo (2006), `hep-ph/0610104`.
3. A. Leike, *Phys. Rept.* **317**, 143–250 (1999), `hep-ph/9805494`.
4. B. Holdom, *Phys. Lett.* **B166**, 196 (1986).
5. E. C. G. Stueckelberg, *Helv. Phys. Acta* **11**, 225–244 (1938).
6. M. Goodsell, J. Jaeckel, J. Redondo, and A. Ringwald, *JHEP* **11**, 027 (2009), `arXiv:0909.0515 [hep-ph]`.
7. B. A. Dobrescu, *Phys. Rev. Lett.* **94**, 151802 (2005), `arXiv:hep-ph/0411004`.
8. J.-H. Huh, J. E. Kim, J.-C. Park, and S. C. Park, *Phys. Rev.* **D77**, 123503 (2008), `arXiv:0711.3528 [astro-ph]`.
9. J. L. Feng, M. Kaplinghat, H. Tu, and H.-B. Yu, *JCAP* **0907**, 004 (2009), `arXiv:0905.3039 [hep-ph]`.
10. S. A. Abel, M. D. Goodsell, J. Jaeckel, V. V. Khoze, and A. Ringwald, *JHEP* **07**, 124 (2008), `arXiv:0803.1449 [hep-ph]`.
11. A. Afanasev *et al.* (2008), `arXiv:0810.4189 [hep-ex]`.
12. **ALPS** Collaboration, K. Ehret *et al.* (2009), `arXiv:0905.4159 [physics.ins-det]`.
13. C. Burrage, J. Jaeckel, J. Redondo, and A. Ringwald, *JCAP* **0911**, 002 (2009), `arXiv:0909.0649 [astro-ph.CO]`.

14. P. Fayet, *Phys. Rev.* **D74**, 054034 (2006), `arXiv:hep-ph/0607318`.
15. C. Boehm and P. Fayet, *Nucl. Phys.* **B683**, 219–263 (2004), `arXiv:hep-ph/0305261`.
16. N. Borodatchenkova, D. Choudhury, and M. Drees, *Phys. Rev. Lett.* **96**, 141802 (2006), `arXiv:hep-ph/0510147`.
17. M. Pospelov (2008), `arXiv:0811.1030 [hep-ph]`.
18. N. Arkani-Hamed, D. P. Finkbeiner, T. R. Slatyer, and N. Weiner, *Phys. Rev.* **D79**, 015014 (2009), `arXiv:0810.0713 [hep-ph]`.
19. R. Sundrum (2009), these proceedings.
20. D. Tucker-Smith and N. Weiner, *Phys. Rev.* **D64**, 043502 (2001), `arXiv:hep-ph/0101138`.
21. N. Arkani-Hamed and N. Weiner, *JHEP* **12**, 104 (2008), `arXiv:0810.0714 [hep-ph]`.
22. S. Gopalakrishna, S. J. Lee, and J. D. Wells (2009), `arXiv:0904.2007 [hep-ph]`.
23. R. Essig, P. Schuster, and N. Toro, *Phys. Rev.* **D80**, 015003 (2009), `arXiv:0903.3941 [hep-ph]`.
24. J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, *Phys. Rev.* **D80**, 075018 (2009), `arXiv:0906.0580 [hep-ph]`.
25. M. Baumgart, C. Cheung, J. T. Ruderman, L.-T. Wang, and I. Yavin, *JHEP* **04**, 014 (2009), `arXiv:0901.0283 [hep-ph]`.
26. C. Cheung, J. T. Ruderman, L.-T. Wang, and I. Yavin (2009), `arXiv:0909.0290 [hep-ph]`.
27. M. Reece and L.-T. Wang, *JHEP* **07**, 051 (2009), `arXiv:0904.1743 [hep-ph]`.
28. D. E. Morrissey, D. Poland, and K. M. Zurek, *JHEP* **07**, 050 (2009), `arXiv:0904.2567 [hep-ph]`.
29. C. Coriano, A. E. Faraggi, and M. Guzzi, *Phys. Rev.* **D78**, 015012 (2008), `arXiv:0802.1792 [hep-ph]`.
30. P. Nath (2008), `arXiv:0812.0958 [hep-ph]`.
31. I. Antoniadis (2009), these proceedings.
32. R. Armillis, C. Coriano', M. Guzzi, and S. Morelli, *Nucl. Phys.* **B814**, 15679 (2009), `arXiv:0809.3772 [hep-ph]`.
33. B. Kors and P. Nath, *Phys. Lett.* **B586**, 366–372 (2004), `arXiv:hep-ph/0402047`.
34. D. Feldman, Z. Liu, and P. Nath, *Phys. Rev. Lett.* **97**, 021801 (2006), `arXiv:hep-ph/0603039`.
35. M. J. Strassler and K. M. Zurek, *Phys. Lett.* **B651**, 374–379 (2007), `arXiv:hep-ph/0604261`.
36. T. Han, Z. Si, K. M. Zurek, and M. J. Strassler, *JHEP* **07**, 008 (2008), `arXiv:0712.2041 [hep-ph]`.
37. Y. Gershtein, F. Petriello, S. Quackenbush, and K. M. Zurek, *Phys. Rev.* **D78**, 095002 (2008), `arXiv:0809.2849 [hep-ph]`.
38. P. Langacker, G. Paz, L.-T. Wang, and I. Yavin, *Phys. Rev. Lett.* **100**, 041802 (2008), `arXiv:0710.1632 [hep-ph]`.
39. H. Verlinde, L.-T. Wang, M. Wijnholt, and I. Yavin, *JHEP* **02**, 082 (2008), `arXiv:0711.3214 [hep-th]`.
40. N. Arkani-Hamed and S. Dimopoulos, *JHEP* **06**, 073 (2005), `arXiv:hep-th/0405159`.
41. J. De Blas, P. Langacker, G. Paz, and L.-T. Wang (2009), `arXiv:2009`.
42. T. Kikuchi and T. Kubo, *Phys. Lett.* **B669**, 81–87 (2008), `arXiv:0807.4923 [hep-ph]`.
43. J. Erler, P. Langacker, S. Munir, and E. R. Pena (2009), `arXiv:0906.2435 [hep-ph]`.
44. V. Barger, T. Han, and D. G. E. Walker, *Phys. Rev. Lett.* **100**, 031801 (2008), `arXiv:hep-ph/0612016`.
45. S. Godfrey and T. A. W. Martin, *Phys. Rev. Lett.* **101**, 151803 (2008), `arXiv:0807.1080 [hep-ph]`.
46. F. Petriello and S. Quackenbush, *Phys. Rev.* **D77**, 115004 (2008), `arXiv:0801.4389 [hep-ph]`.
47. V. Barger, P. Langacker, and H.-S. Lee (2009), `arXiv:0909.2641 [hep-ph]`.
48. M. Maniatis (2009), `arXiv:0906.0777 [hep-ph]`.
49. V. Barger, P. Langacker, H.-S. Lee, and G. Shaughnessy, *Phys. Rev.* **D73**, 115010 (2006), `arXiv:hep-ph/0603247`.
50. E. Accomando *et al.* (2006), `arXiv:hep-ph/0608079`.
51. V. Barger *et al.*, *Phys. Rev.* **D75**, 115002 (2007), `arXiv:hep-ph/0702036`.
52. J. Kang, P. Langacker, and B. D. Nelson, *Phys. Rev.* **D77**, 035003 (2008), `arXiv:0708.2701 [hep-ph]`.

53. S. F. King, S. Moretti, and R. Nevzorov, *Phys. Rev.* **D73**, 035009 (2006), `arXiv:hep-ph/0510419`.
54. J. Kang and P. Langacker, *Phys. Rev.* **D71**, 035014 (2005), `arXiv:hep-ph/0412190`.
55. M. Baumgart, T. Hartman, C. Kilic, and L.-T. Wang, *JHEP* **11**, 084 (2007), `arXiv:hep-ph/0608172`.
56. T. Cohen and A. Pierce, *Phys. Rev.* **D78**, 055012 (2008), `arXiv:0803.0765 [hep-ph]`.
57. H.-S. Lee, *Phys. Lett.* **B674**, 87–91 (2009), `arXiv:0812.1854 [hep-ph]`.
58. A. Ali, D. A. Demir, M. Frank, and I. Turan, *Phys. Rev.* **D79**, 095001 (2009), `arXiv:0902.3826 [hep-ph]`.
59. P. Langacker and M. Plumacher, *Phys. Rev.* **D62**, 013006 (2000), `arXiv:hep-ph/0001204`.
60. V. Barger *et al.* (2009), `arXiv:0906.3745 [hep-ph]`.
61. J.-h. Kang, P. Langacker, and T.-j. Li, *Phys. Rev.* **D71**, 015012 (2005), `arXiv:hep-ph/0411404`.
62. S. King (2009), these proceedings.
63. R. Mohapatra (2009), these proceedings.
64. J. Valle (2009), these proceedings.
65. D. A. Demir, L. L. Everett, and P. Langacker, *Phys. Rev. Lett.* **100**, 091804 (2008), `arXiv:0712.1341 [hep-ph]`.
66. R. Blumenhagen, M. Cvetic, S. Kachru, and T. Weigand (2009), `arXiv:0902.3251 [hep-th]`.
67. M. Cvetič (2009), these proceedings.
68. P. F. Perez and S. Spinner (2009), `arXiv:0909.1841 [hep-ph]`.
69. J. Kang, P. Langacker, T.-j. Li, and T. Liu, *Phys. Rev. Lett.* **94**, 061801 (2005), `arXiv:hep-ph/0402086`.